An Integrated Inherent Optical Property Sensor for AUVs

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LONG TERM GOALS

Several automated, compact sampling platforms have recently been developed or are gaining widespread use in Naval operations and oceanographic research for mapping environmental parameters in multiple dimensions. In addition to limited sensor payloads, many of these platforms are intended for extended deployments. Sensors compatible with these platforms must therefore be compact and low power. Developing optical sensors with these qualities for use in Naval operations and oceanographic research is a core long term goal.

OBJECTIVE

Low power/volume/cost optical sensors compatible with compact AUVs have now been developed for measuring beam attenuation, c, and backscattering, b_b. Our objective is to develop an AUV-compatible device measuring total scattering, b, that would then allow absorption, a, to be derived from $c - b$ (note $c = a + b$).

APPROACH

Sensing technology to measure a or b is currently the missing component to simultaneously measuring $a, b, c,$ and b_b with a low power/volume/cost, AUV compatible sensor. We pursued the development of a b meter because initial promising designs were most compatible with design criteria. Our approach in Phase-I work was:

1) To conduct a modeling effort to determine the optimal design for a b sensor, and

2) To use this design along with previous proprietary technological innovations to develop a prototype AUV-compatible scattering sensor that makes a measurement highly correlated with b.

Modeling work clearly indicated that an approach we are calling the Inverted Beutell – Brewer (IBB) method was optimal. This method uses a diffuse detector looking normal to a collimated source beam to approximate a sin(θ) angular weighting for scattered light from ~0 to ~π radians, an inverse arrangement to the scattering sensor originally proposed by Beutell and Brewer (1949). This geometry provides a quasi-sin(θ) shape to the weighting function (angular sensitivity of the scattering measurement), which matches the sine weighting of the volume scattering function (VSF) used in

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determining b ($b = 2\pi\int_0^\pi \sin(\theta)\beta(\theta)d\theta$, where β is the VSF). In theory, the resultant measurement of the VSF is thus weighted equally over all angles. ***Consequently, the measurement of total scattering exhibits no dependence on the shape of the VSF*** (verified in lab experiments below). The only VSF dependence would be on the relative contribution of the extreme near-forward scattering (<~0.9 degrees), a dependence that is also characteristic of all attenuation meters.

The next step in the project was experimental verification of the analytical modeling results where the various assumptions made in modeling efforts (e.g., homogeneous source and detector beams, idealized acceptance angles, single scattering only, etc.) are subject to practical implementation. A prototype testbed enabling measurements of various possible approaches with varying geometrical properties was fabricated that allowed this evaluation. The testbed allowed an evaluation of the theory and the model under a wide range of conditions.

The approach through the past year has involved development and testing of the AUV-B beta-prototype based on the previous evaluations with the testbed. Several iterative design upgrades have been implemented from ongoing extensive testing. Many of the design upgrades were made in the context of enabling a smoother transition to a commercial product.

WORK COMPLETED

• Refined AUV-B calibration protocol with a look-up table inversion

• Developed easy-to-use graphical user interface (GUI) to process AUV-B data, implement calibration

• Modified placement of circuit boards and some optics in AUV-B to accommodate slocum glider payload bay with two ECO pucks; modified data output format for slocum glider

• Improved design of AUV-B detector diffuser to avoid delamination and tested

• Researched, designed and fabricated a 532 nm AUV-B

• Modified AUV-B design to simplify time consuming optics alignment and assembly in the context of future production

• Investigated a problem with reference drift that was traced to thermal dependencies in the performance of optical components used in the laser source assembly

• Manufactured four 650 nm AUV-B sensors for installation in slocum gliders for SSC NRL

• The AUV-B sensor and results were presented at Ocean Optics in Montreal, October 2006

• Integrated and deployed AUV-B sensors on a host of different platforms to assess performance, including:

- ship vertical profiling package (Penobscot Estuary, Maine; Pacific Ocean off Lanai Island, Hawaii; Northwest Atlantic; NY bight region),
- undulating tow vehicle (DOLPHIN),
- automated winch controlled profiling system (Narragansett Bay, RI and Martha's Vineyard Coastal Observatory),
- Rutgers University (Schofield and Glenn) slocum glider AUV (Martha's Vineyard Coastal Observatory), and
- SSC-NRL slocum glider AUV (Florida coast).

RESULTS

To recap, the response of the AUV-B as a function of *b* is plotted in **Fig. 1**. The equation in **Fig. 1** must be inverted to solve for *b*. The calibration algorithm now achieves this with a universal look-up table where a scaling factor scales all the pertinent values in the table. A unique look-up table does not have to be created for each sensor calibration, which facilitates eventual transition of the protocol to a production team. Processing software with GUI compiled in MATLAB was developed to apply calibrations to collected data using a sensor-specific device file.

Several iterative upgrades to the AUV-B optics, electronics, and mechanical design have been carried out in the past year as a result of extensive testing. These are summarized below.

Diffuser

Teflon is used for the detector diffuser because of close refractive index matching with seawater. Long-pass filtered glass is used at the top of the detector assembly to reject ambient light and the Teflon must interface with this glass. The first design relied on clear silicone glue bonding of the Teflon to the glass. After field use, partial delamination of the Teflon was observed. A mechanical bolt-on version was then tried, using silicone grease to make a non-bonding seal between the diffuser and filter. This version did not exhibit delamination under testing, and showed similar thermal and optical stability relative to the silicone bonding, but concerns were expressed over robustness and the effects of pressure. A third option was then tried: a Teflon product that has one bondable surface. The bondable surface was a translucent brown, but this abraded away easily, making a diffusing window surrounded by bondable material. After extensive testing over large temperature and pressure ranges, no delamination of the Teflon diffuser occurred.

Optical Path

Several modifications were made to simplify the optical path, improve alignment process, and eliminate stray light. Adjustment mechanisms for laser alignment required space that was precious or unavailable if the current form factor was to be maintained. Furthermore, the reference detector, beam

splitter, and several air-glass interfaces were sources of stray light. The first modification to the original design was to use a dove prism periscope to eliminate a pair of prisms and also the pressure window. This eliminated four air-glass interfaces, which are sources of stray light and opportunities for misalignment. The prism is potted thru the faceplate so that ambient pressure acts on the cross-section of the prism, rather than the exposed (window) face of it. This allows for a very strong window with depth rating much greater than 1000 m. Second, beam splitter support was added to three sides instead of just one, making it more stable and durable. The beam splitter mount was also beveled to reduce stray light. The reference detector was deflected to the side and is angled with respect to the reflected beam so that light reflected by the detector face can be disposed of in a non-critical region. Finally, a pair of wedge prisms was installed for laser alignment that rotate independently to steer the beam, allowing the laser to be simply fixed onto the face of the dove prism. The updated design is shown in **Fig. 2**.

Problems with drifting reference counts were identified and addressed in a series of extensive tests and subsequent design modifications. The drift appeared to be due to transmission changes of some optical components due to heating. Replacing these components and using a reflection off the first surface of one of the alignment prisms as a reference beam solved the problem.

Components were also added to protect the AUV-B optics during handling and installation into compact platforms. Previous hard plastic shields were replaced with an EPDM foam rubber tube that slips over the laser and seals against the cube beamsplitter (**Fig. 3**). This provided the same protection while occupying less volume in payload bays. Bump guards were also added for certain components.

The "green solution"

Past attempts to build 532 nm sensors with a laser source have been stymied by the limited temperature range of commercial 532 nm laser diodes. The output from these lasers decreases dramatically with temperature and is unusable below about 12 deg C. We have found a new COTS laser, however, that has a thermoelectric temperature regulation component to maintain operational temperatures in a viable range despite ambient temperatures as low as 0 deg C. When the thermal regulation is not required, the current draw for the AUV-B is comparable to that with the red laser. When the thermal regulation is active, current draws increase to ~400 mA, comparable to the CTD used on the Slocum gliders.

The mechanical, electrical and data handling integration was completed for the green laser. Two green laser AUV-B prototypes have been manufactured to date with two more in queue. One of these green AUV-B's is currently deployed on a Rutgers University Slocum glider at the Martha's Vineyard Coastal Observatory for the OASIS project.

SAM redesign

The SAM design was also updated to accommodate the 532 nm laser diode source and to improve manufacturability and durability. The primary design changes were a revision of the faceplate design and modifying the components of the laser mount assembly. A 532 nm SAM is currently in development.

AUV-B testing results

With the current tuning protocol, the AUV-B detector begins to saturate at a b of about 4 m^{-1}, with an accuracy of 3-4% maintained over the entire range. Field results continue to demonstrate good

correspondence with independent ac9 measurements (**Fig. 4**). Processing of data from all the deployments of the AUV-B over the past year continue. We are preparing to add this data to the analyses carried out for the Ocean Optics Conference last October in the form of a journal submission. During the OASIS deployment that ended 9/21/07, we collected over 300 automated vertical profiles of optical measurements, including AUV-B data.

IMPACT/APPLICATIONS

Progress and results represent important steps toward the development of a compact, flat face sensor measuring *a, b, c,* and b_b for Naval operations and oceanographic research. Knowledge of the Inherent Optical Properties of water can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. These measurements are also widely used in environmental monitoring and research applications for determining particle concentration, particle composition, and water clarity.

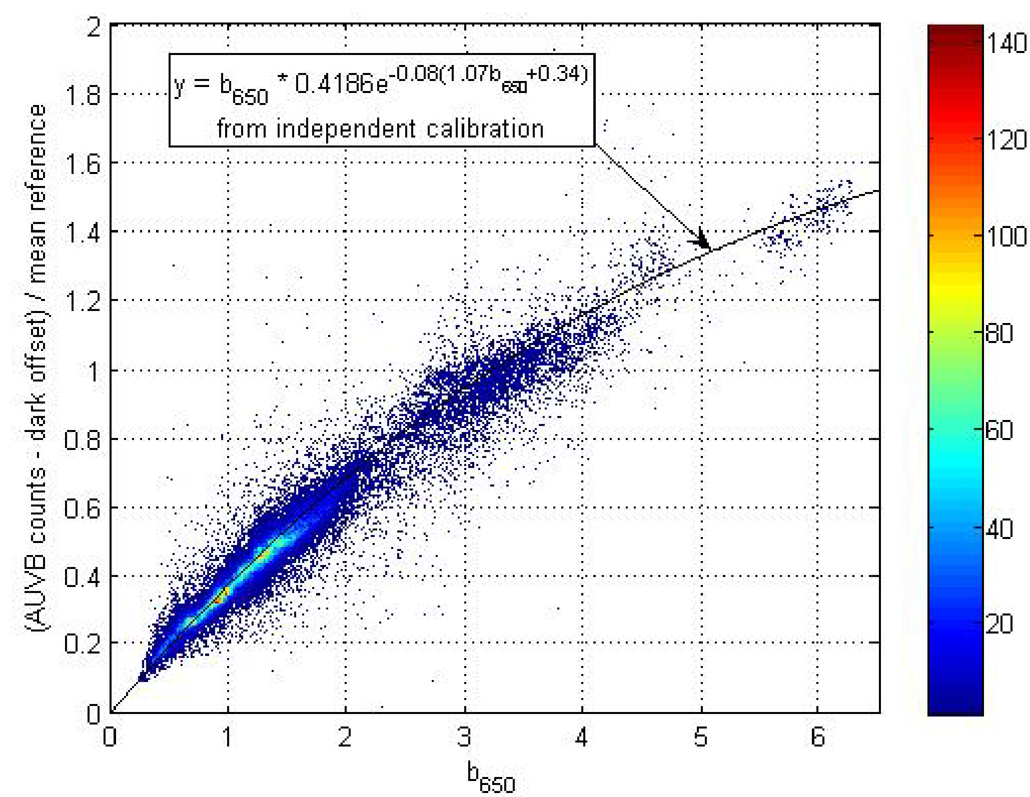

Figure 1. Comparison of the raw digital counts measured with the AUV-B sensor to the particulate scattering measured with an ac9. Two data sets are shown: a lab calibration with Arizona Road Dust and field measurements from Long Island Sound. Only the model fit of the lab calibration is plotted, where signal = b*exp(-cl), the theoretical expectation. The values 0.4186, 0.08, 1.07, and 0.34 correspond to the scaling factor derived from the calibration, the effective pathlength in m, the multiple of b(650) to add an empirically determined 7% particulate absorption, and the absorption coefficient of pure water at 650 nm. All of these parameters are fixed except the scaling factor. The independent data sets agree well, demonstrating that the lab calibration is effective and the two sets of results closely follow the theoretical expectation.

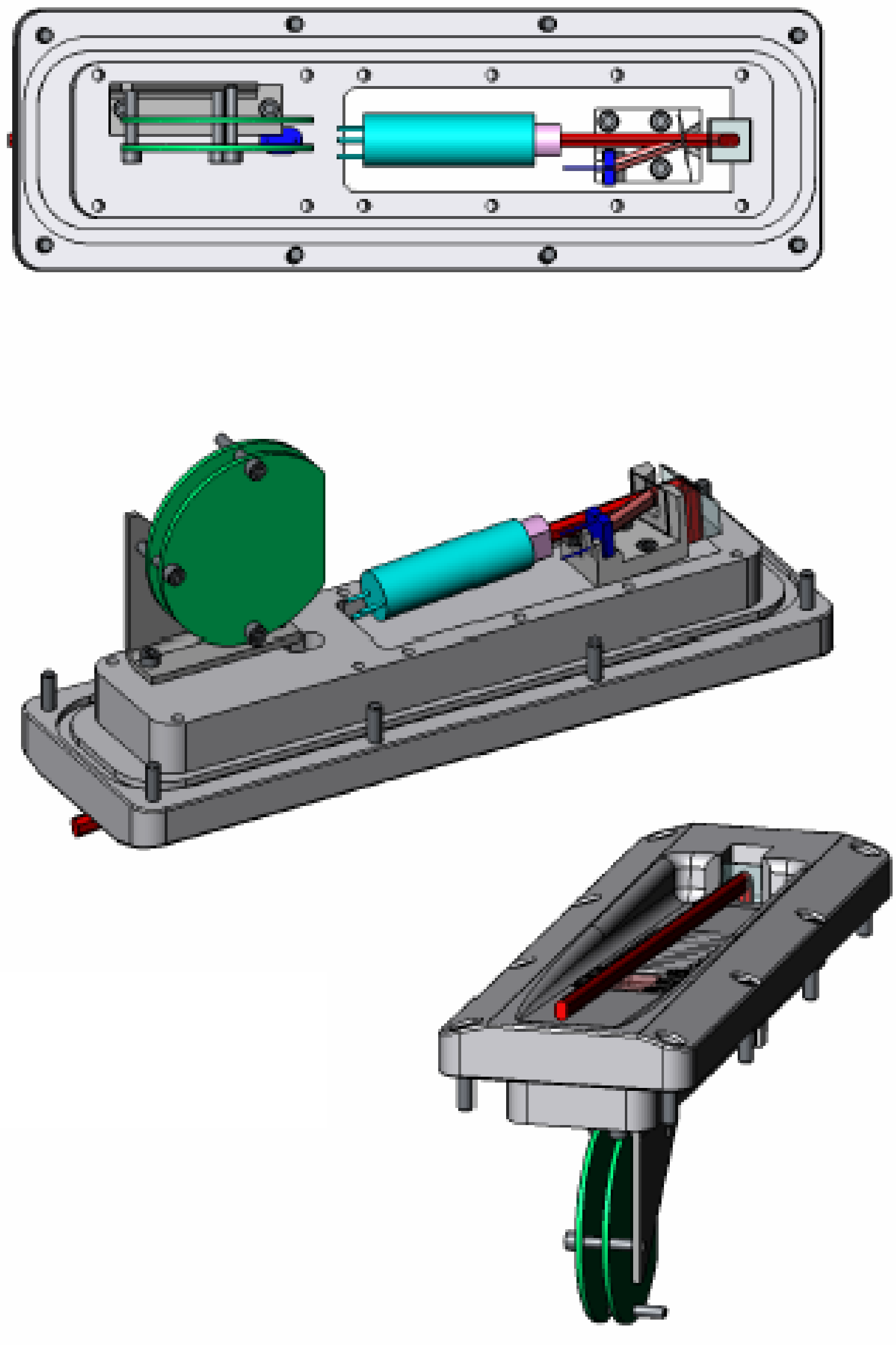

Figure 2. Updated AUV-B design with dove prism and off-axis reference.

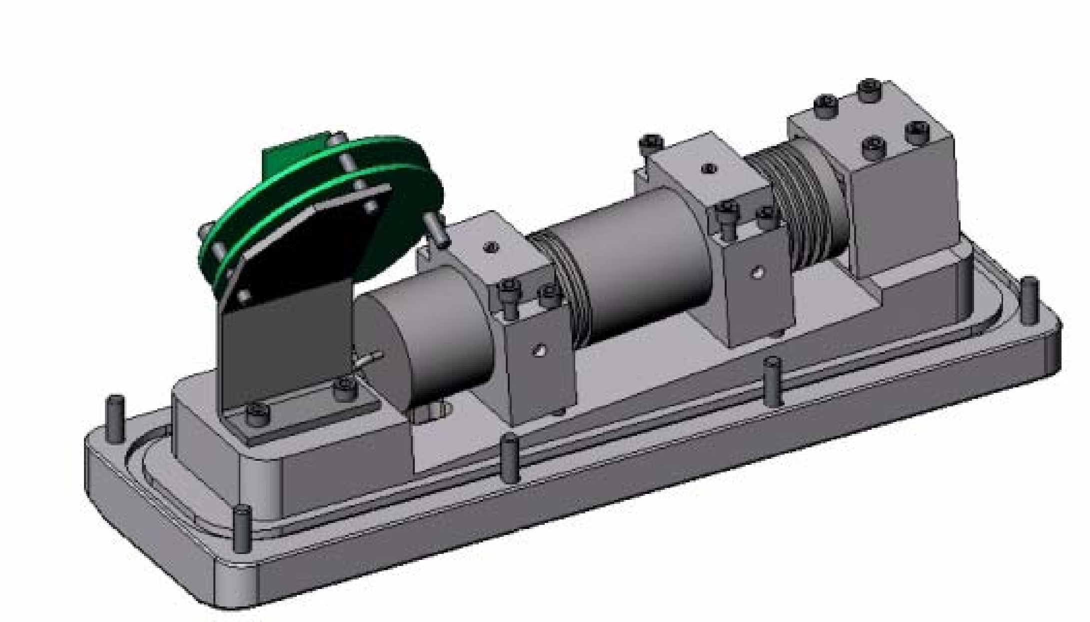

Figure 3. AUV-B interior with optical protection jackets installed.

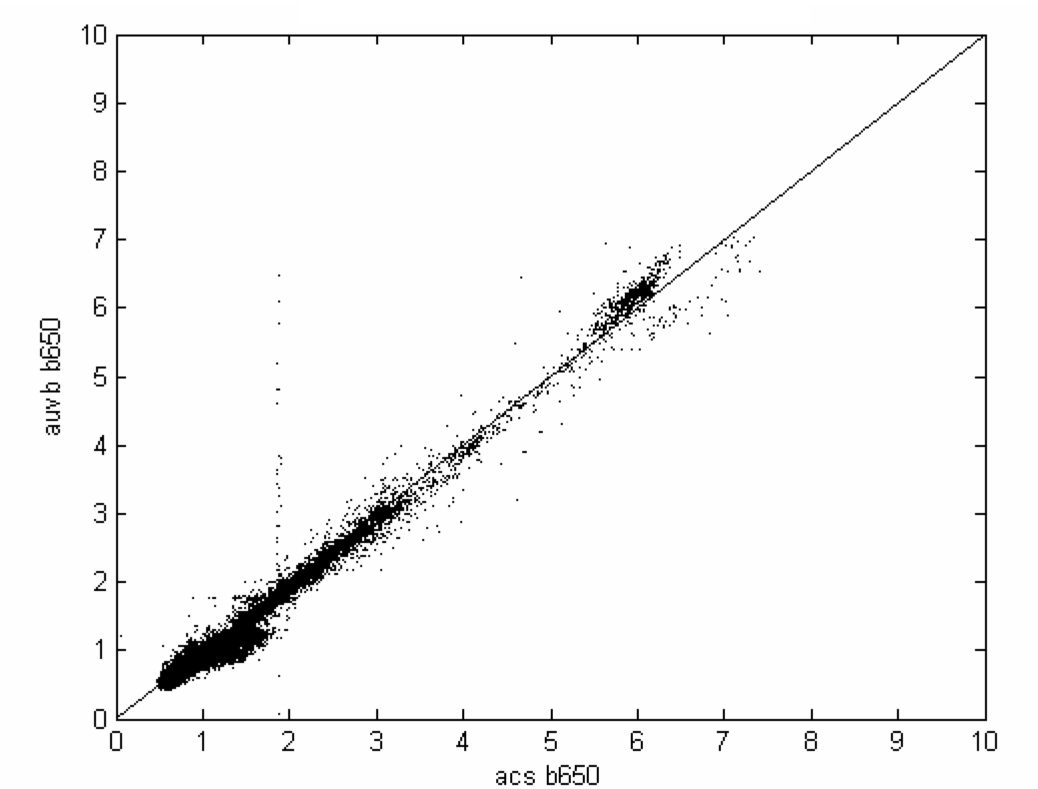

Figure 4. Independently calibrated AUV-B b(650) measurements as a function of AC-S b(650) measurements collected on the DOLPHIN towed vehicle in the Penobscot Estuary, Maine in October 2006.

TRANSITIONS

We expect that our efforts in developing optical sensors for automated deployment platforms and our success in integrating these sensors on such platforms will lead to transition of these optical sensors into operational tools for the fleet and the oceanographic research community in the future. These sensors are currently being used on automated platforms in Naval mine countermeasure exercises such as RIMPAC and in ONR research initiatives such as OASIS and RADYO. Slocum gliders equipped with the AUV-B or SAM are used in academic research (Rutgers University and North Carolina University), in recently delivered NRL slocum gliders, and in recently ordered Naval Oceanographic Office gliders.

RELATED PROJECTS

This effort is an extension of ongoing efforts to develop compact optical sensors for AUVs and associated biogeochemical inversion techniques. Related projects include:

- resolving the optics and dynamics of subsurface bubble populations in the Southern Ocean,

- developing a VSF measurement device called the Multiple Angle SCattering and Optical Transmission (MASCOT) sensor,

- developing novel harbor security monitoring capabilities with Chuck Trees and Jim Mueller,

- developing improved vicarious calibration and validation methods for ocean color satellite remote sensing,

- investigating the sources of backscattering in natural waters,

- developing tools for ocean observing systems, and

- developing a surfzone optical mine countermeasure drifter.

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PATENTS

Scattering attenuation meter (SAM), pending.

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